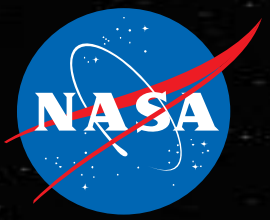
National Aeronautics and Space Administration
Marshall Space Flight Center



Key Quality Assurance Metrics in Additive Manufacturing

Doug Wells
NASA MSFC
Huntsville AL

NASA Quality Assurance in Additive Manufacturing
A Workshop on Assuring AM Product Integrity

Beckman Auditorium, Cal Tech
Pasadena, CA

October 11-12, 2016

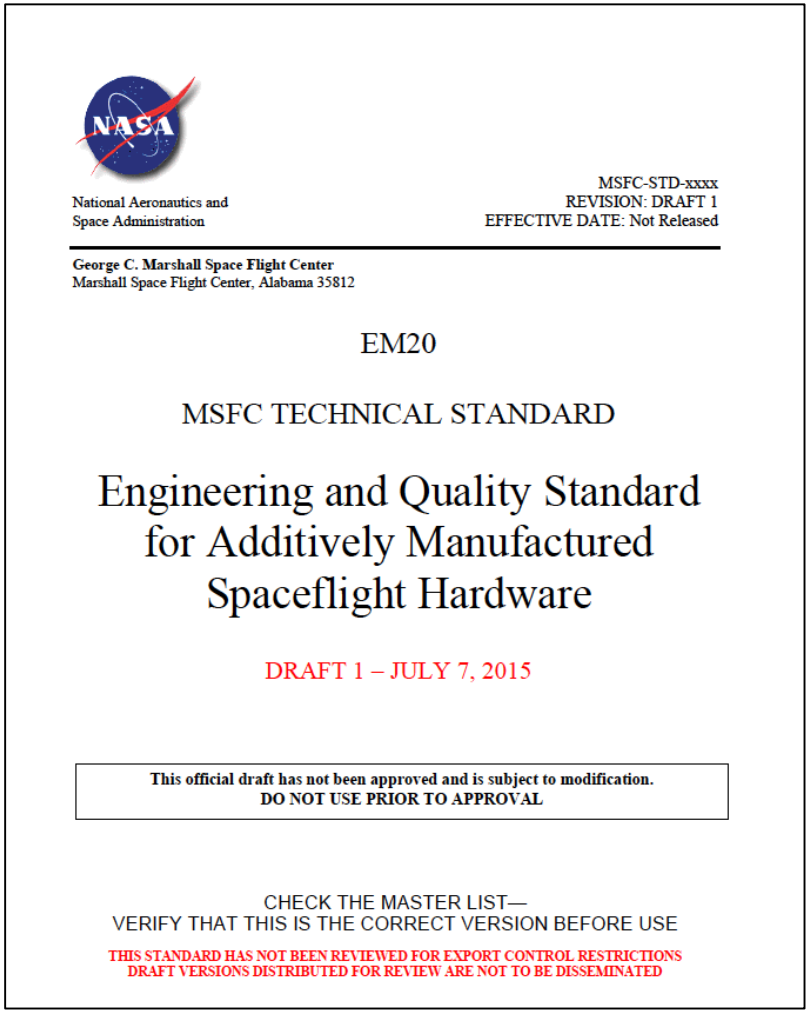
Summary of Points

1. Assuring AM product integrity requires process control rigor:
   - Clear definition of the AM process and its metrics
   - Continuous evaluation of the AM process relative to metrics

2. Open loop AM technologies rely upon passive observation of metrics or post-build evaluation of witness specimens
   - Evolving AM monitoring technologies will provide better methods

3. Selected key metrics within the AM process
   - Qualified Metallurgical Process Record
     - Foundational
     - Defines key metrics for evaluation of the process
   - Witness testing for process control
     - Needs to be adequate and intelligent

Standardization for AM Qualification



National Aeronautics and Space Administration

MSFC-STD-xxxx
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

This official draft has not been approved and is subject to modification.
DO NOT USE PRIOR TO APPROVAL

CHECK THE MASTER LIST—
VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED

Release target:
December 2016

- Draft NASA MSFC Standard
- Methodology for qualification of AM parts and processes for critical applications
  - Space Launch System
  - Commercial Crew Program

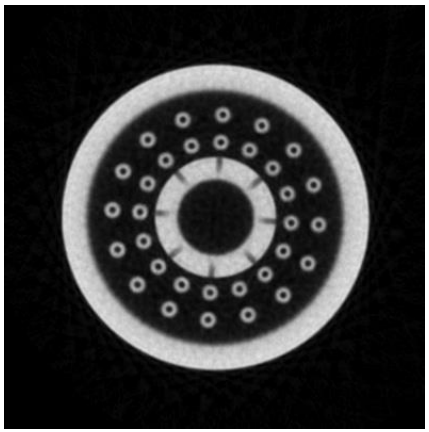
Aerojet Rocketdyne RS-25

SpaceX SuperDraco

Aspects of Process Control

Draft NASA MSFC Standard implements four fundamental aspects of process control for AM:

Metallurgical Process Control



Part Process Control

Equipment Process Control

Build Vendor Process Control

- Each aspect of process control has an essential role in the qualification of AM processes and parts and certification of the systems in which they operate.
- The standard provides a consistent framework for these controls and provides a consistent set of review/audit products

Overview of AM Standard

Design for AM:
Part Development Plan
[PDP]

- **Part Classification**
- Process Definition
- **Integrity Rationale**

Integrity Assessment
NDE/Proof/PC

Build Trials > Dev Articles > First Article | **Production**

Design Value Suite
[DVS]

Validation
[MRR]

Qualified
Part Process
[QPP]

Process
Control
Witness
Evaluations
- Mechanical
- Macro

Registration

Qualified
Metallurgical
Process [QMP]
- Feedstock
- Fusion Process
- Internal quality*
- Surface/Detail Rendering*
- Thermal Processing
- Mechanical Properties*

*acceptance metrics

Process Control
Reference Distributions
[PCRD]

Quality Management System [QMS] Equipment Control Plan [ECP]

Products of the Standard

PDP = Part Development Plans (Overview and implementation)
- Communication, convey risk
- Classification and rationale

DVS = Design Value Suite (properties database)
- “Allowables,” integrated through PCRDs

QMP = Qualified Metallurgical Process (foundational control)
- Analogous to a very detailed weld PQR

PCRD = Process Control Reference Distribution
- Defined reference state to judge process consistency

FAI = First Article Inspection

MRR = Manufacturing Readiness Review

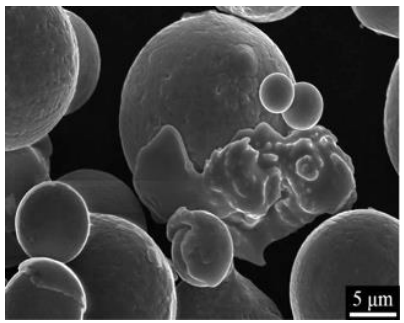
QPP = Qualified Part Process
- Finalized “frozen” part process

ECP = Equipment Control Plans
- Machine qual, re-qual, maintenance, contamination control

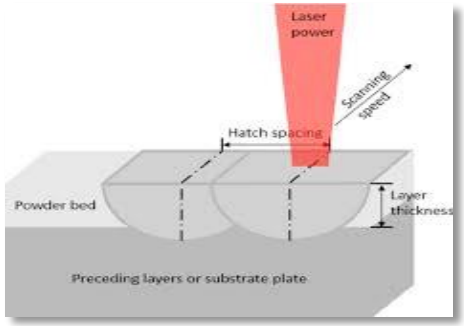
QMS = Quality Management System
- Required at AS9100 level with associated audits

Foundation: Qualified Metallurgical Process

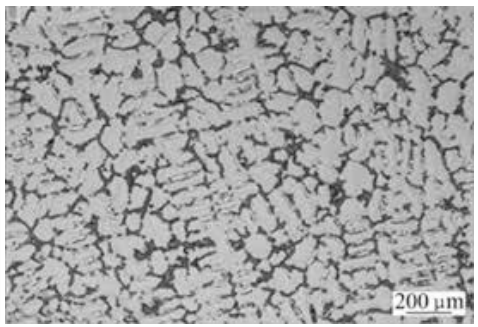
- Draft NASA MSFC Standard identifies AM as a unique material product form and requires the metallurgical process to be qualified on ***every*** individual AM machine
- Developed from internal process specifications with likely incorporation of forthcoming industry standards.



Powder



Process Variables



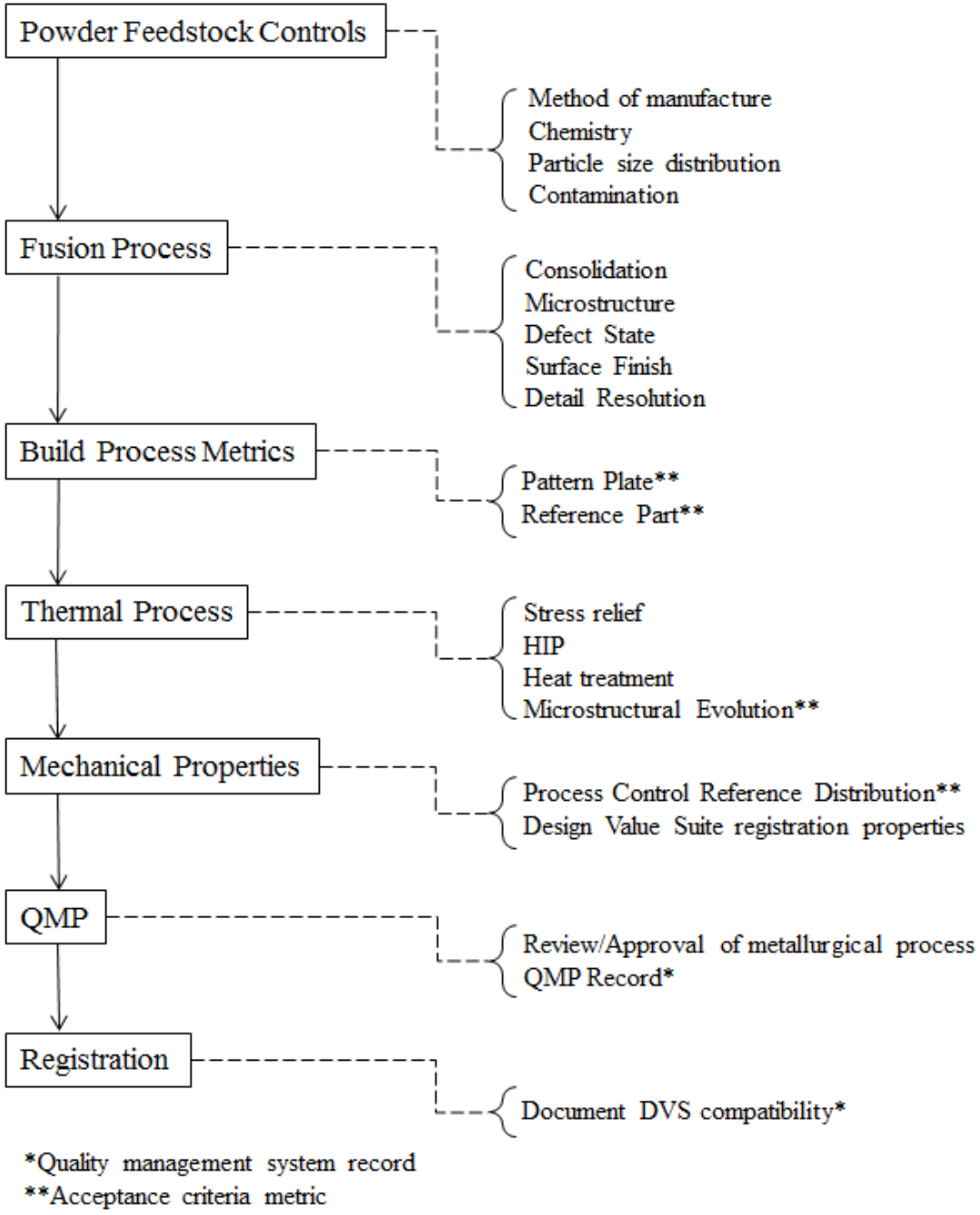
Microstructure

Properties

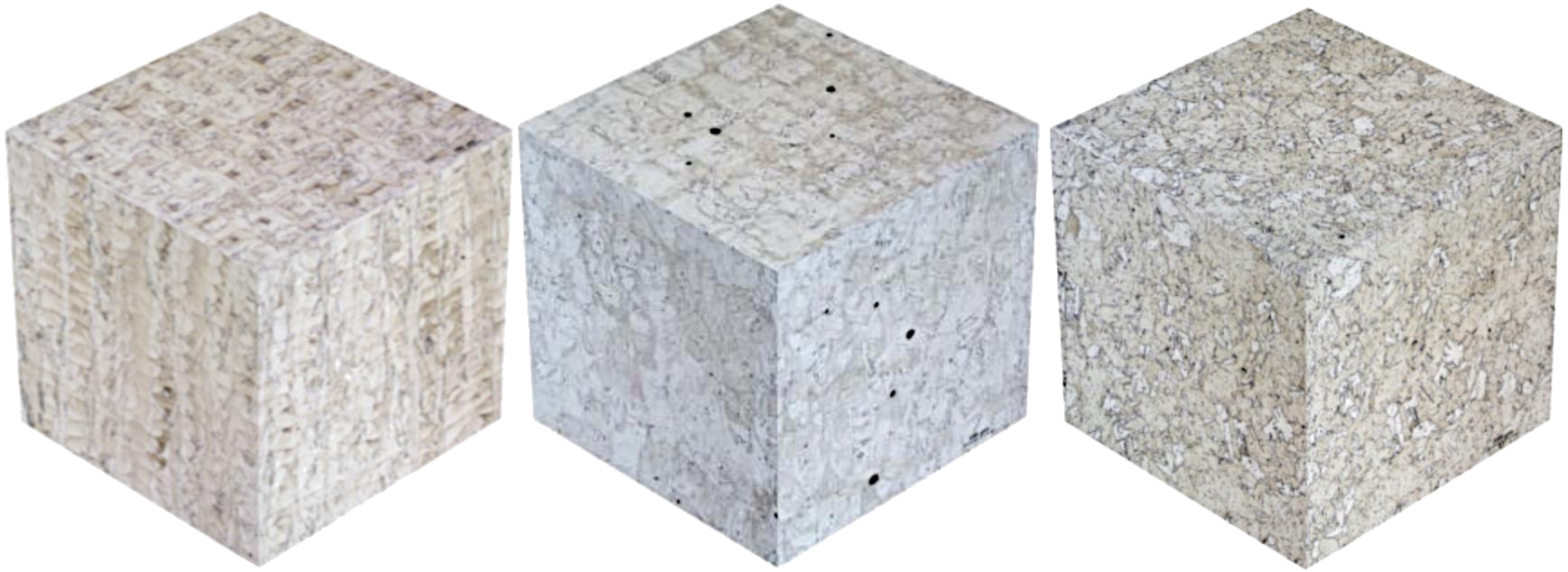
Foundation: Qualified Metallurgical Process

Qualified Metallurgical Process (QMP)

- Feedstock control or specification
- AM machine parameters, configuration, environment
- As-built densification, microstructure, and defect state
- Control of surface finish and detail rendering
- Thermal process for controlled microstructural evolution
- Mechanical behavior reference data
  - Strength, ductility, fatigue performance



Foundation: Qualified Metallurgical Process

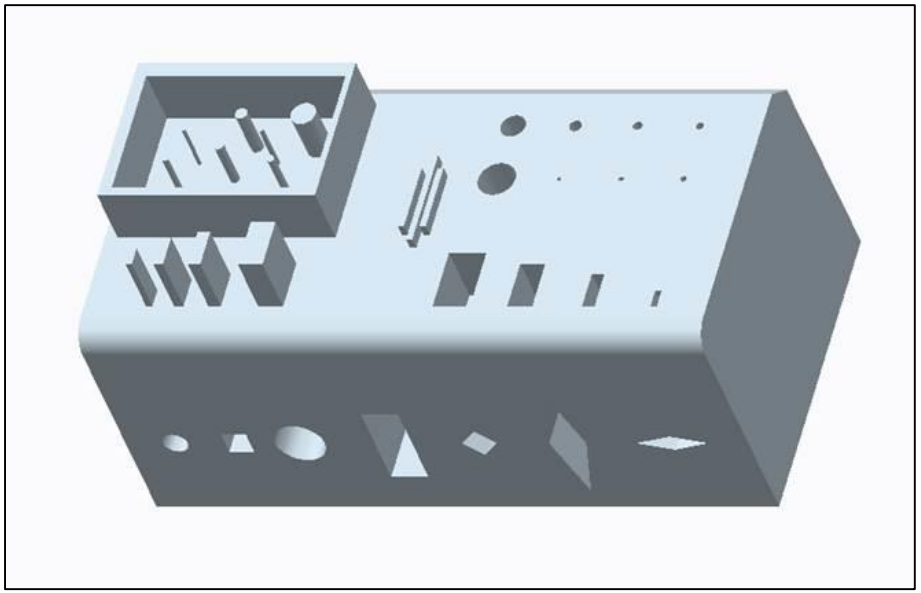


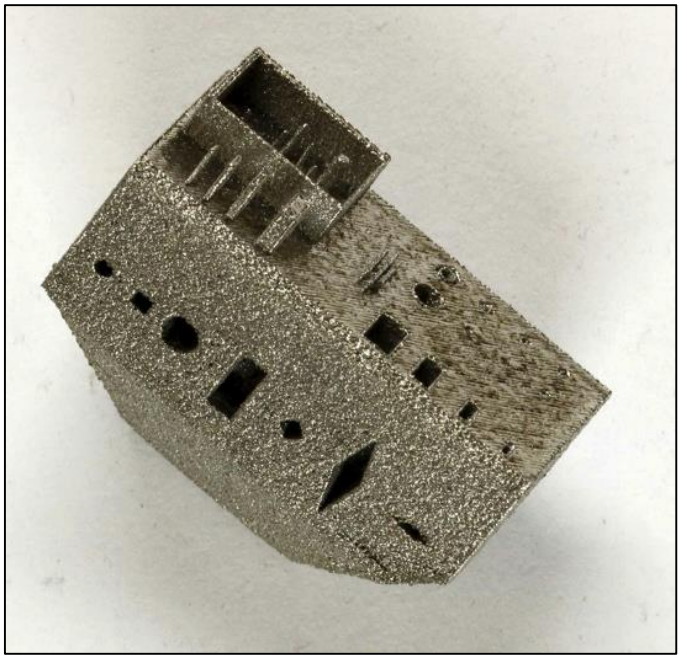
As Built | Stress Relieved | HIP & Final

Qualified Metallurgical Process (QMP)

- As-built densification, microstructure, and defect state
- Thermal process for controlled microstructural evolution

Foundation: Qualified Metallurgical Process





Reference parts:

Metrics for surface texture quality and detail rendering

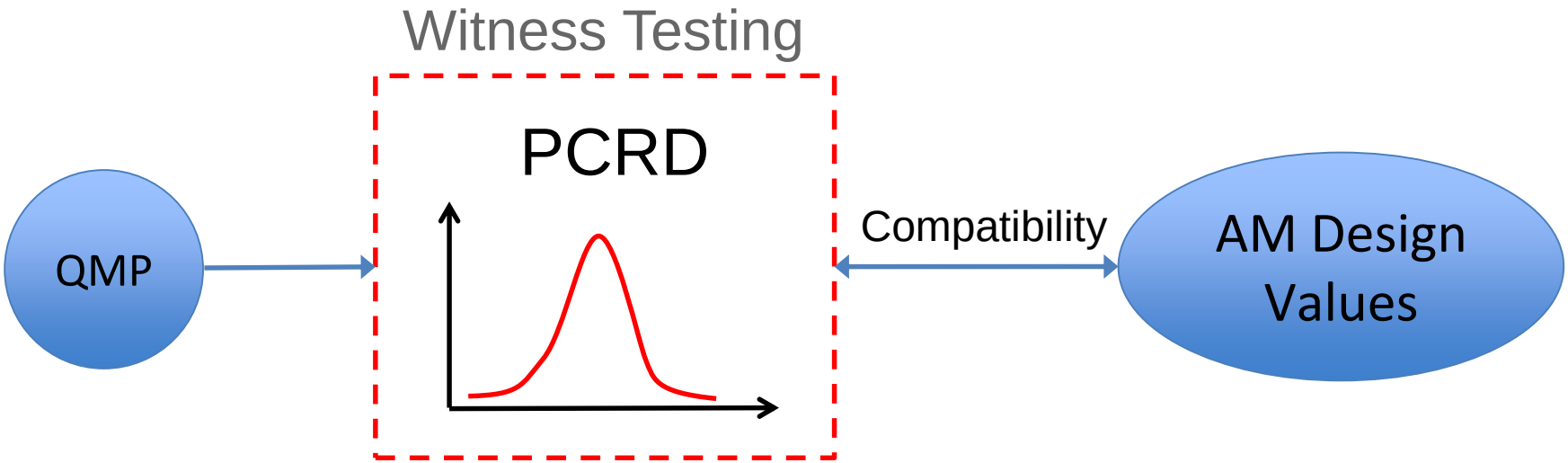
Overhanging, vertical and horizontal surface texture, acuity of feature size and shape

Qualified Metallurgical Process (QMP)

- Reference Parts
- Control of surface finish and detail rendering
- Critical for consistent fatigue performance if as-built surfaces remain in part

Foundation: Qualified Metallurgical Process

- Mechanical behavior reference data
  - Strength, ductility, fatigue performance
  - Process Control Reference Distributions (PCRD)
- Establish and document estimates of mean value and variation associated with mechanical performance of the AM process per the QMP
  - May evolve with lot variability, etc.
- Utilize knowledge of process performance to establish meaningful witness test acceptance criteria



Foundation: Qualified Metallurgical Process

Types of AM build witness specimens

- Metallurgical
- Tensile (strengths and ductility)
- Fatigue
- Low-margin, governing properties (as needed)

What is witnessed?

- Witness specimens provide direct evidence only for the systemic health of the AM process during the witnessed build
- Witness specimens are only an in-direct indicator of AM part quality through inference.

Foundation: Qualified Metallurgical Process

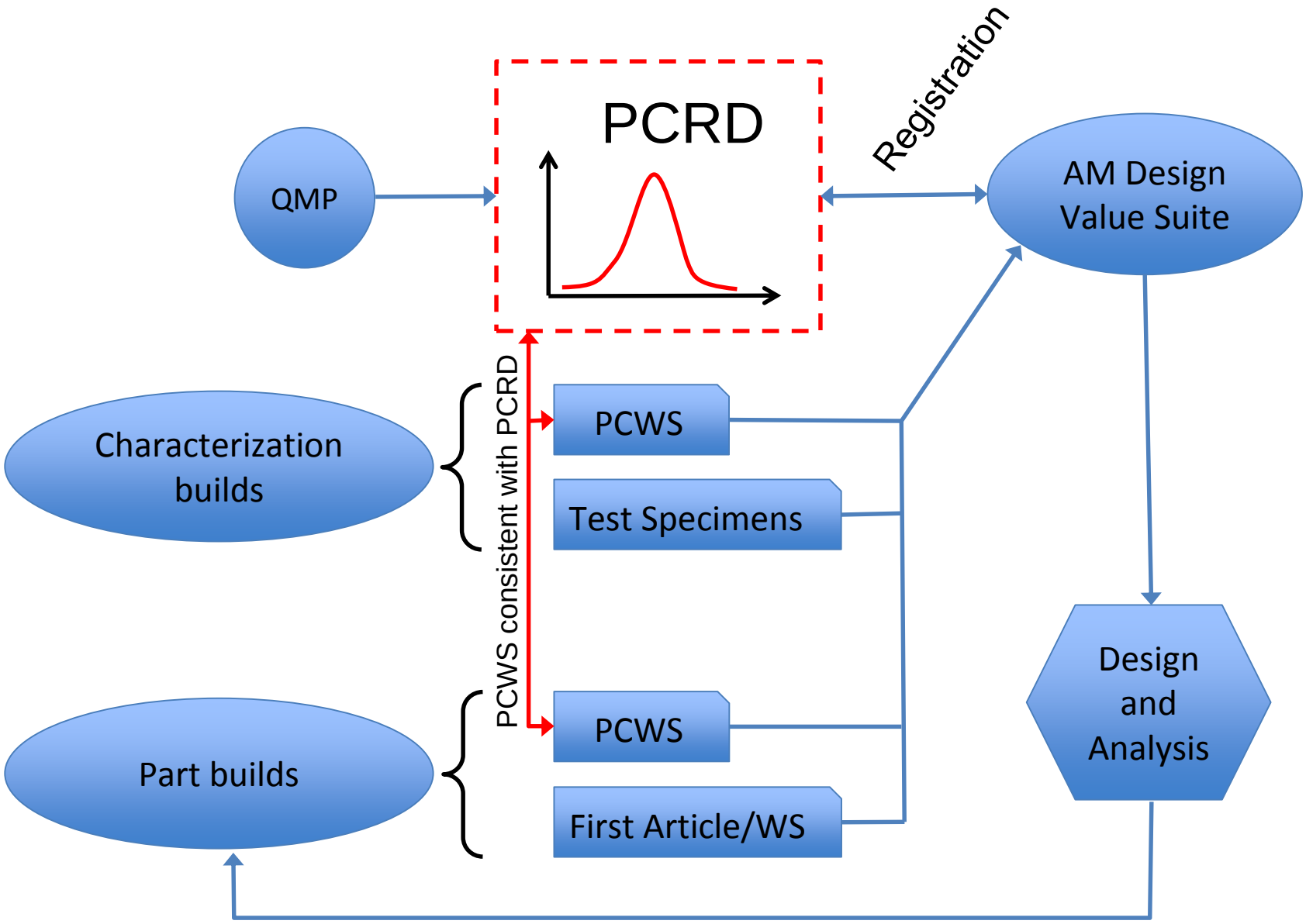
Mechanical Property Witness Procedures

- Move away from spot testing for acceptance against 99/95 design values or specification minimums
- Evaluate with sufficient tests to determine if the AM build is within family
- Compromise with reasonable engineering assurance
- Proposed
  - Six tensile
  - Two fatigue

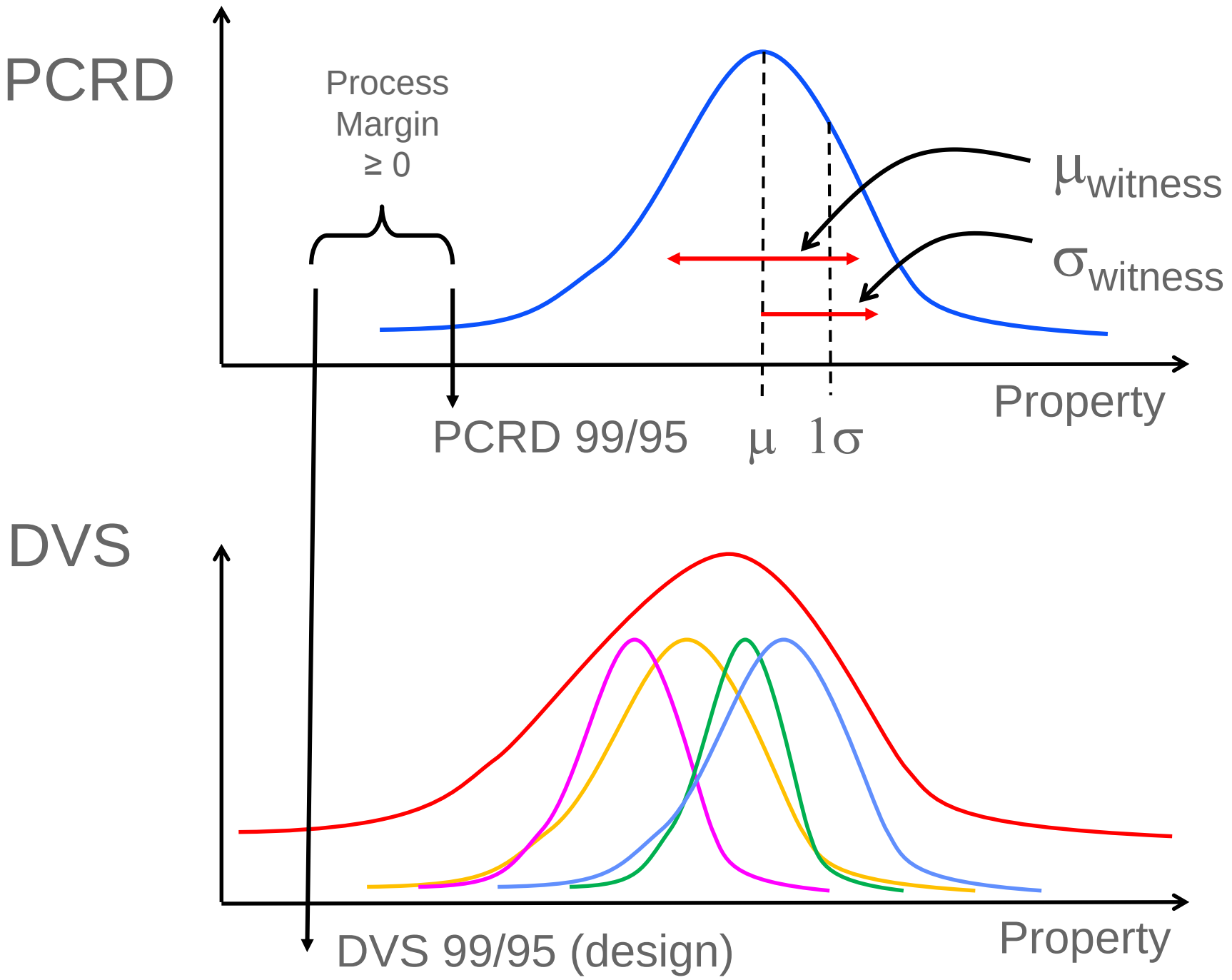
Evaluate against the PCRD of the QMP

- **Ongoing evaluation of material quality substantiates the design allowable**
- **Only plausible way to maintain design values**

Witness for Statistical Process Control



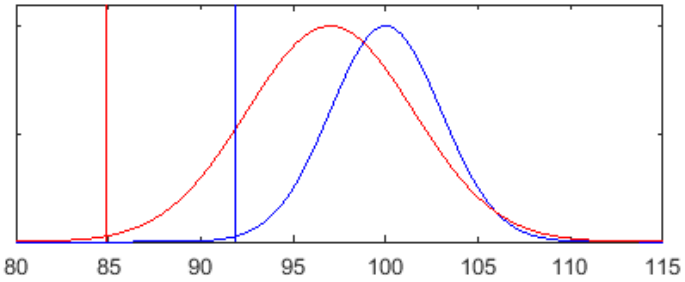
Foundation: Qualified Metallurgical Process



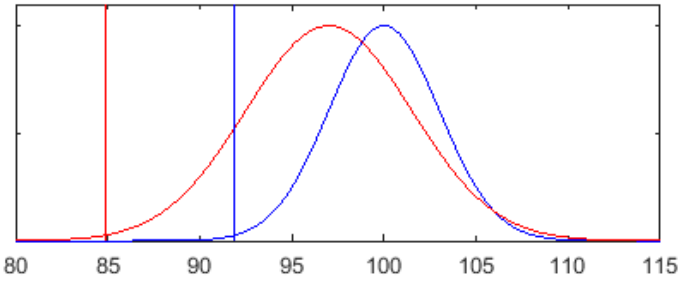
Witness for Statistical Process Control

Example of AM build witness specimen evaluations

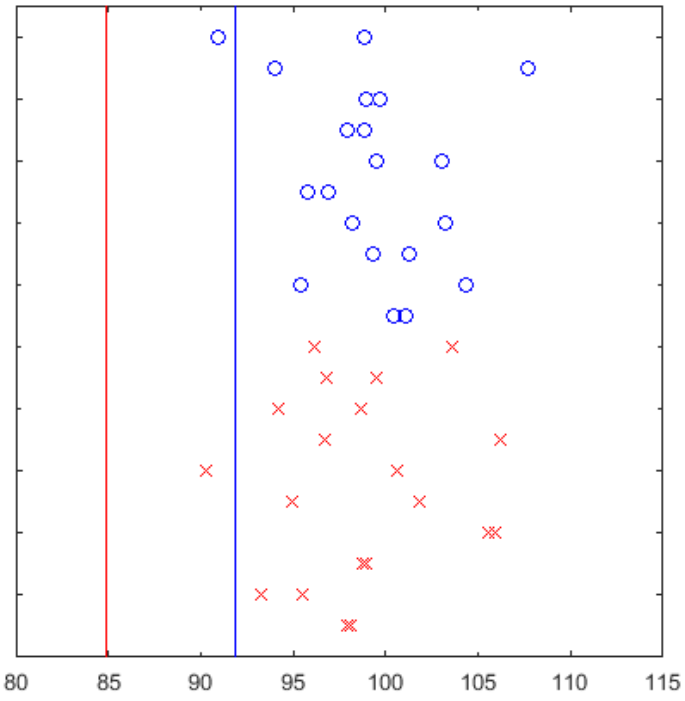
Nominal process is blue, off nominal in red



Two (2) witness tests per build



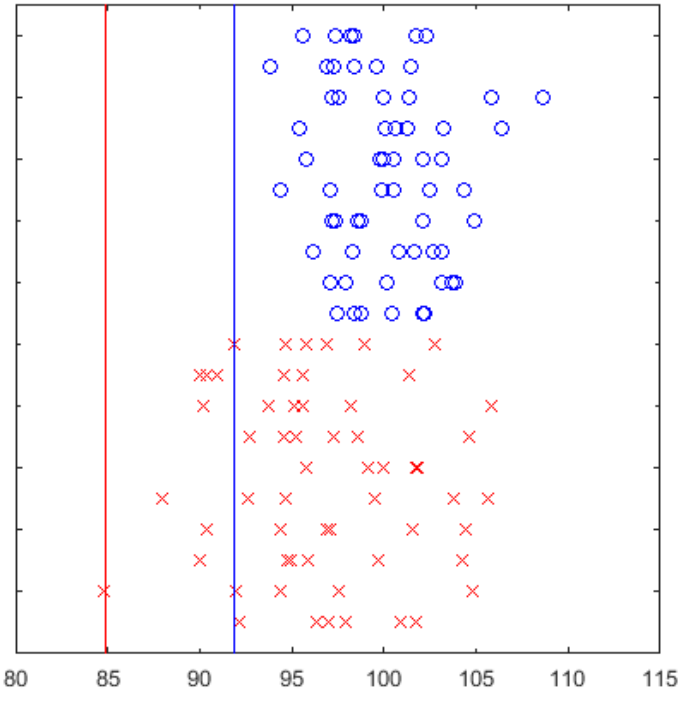
Six (6) witness tests per build



Process shift hard to discern

Random draw from nominal process 10 times

Random draw from off-nominal process, 10 times



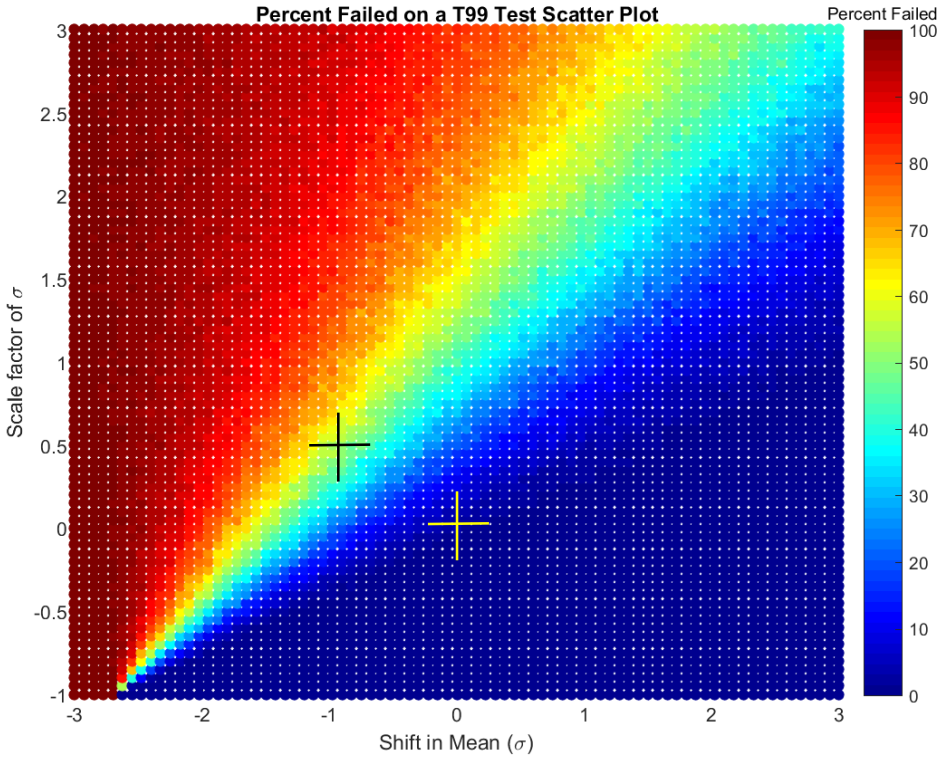
Process shift discernable with analysis of mean and variation

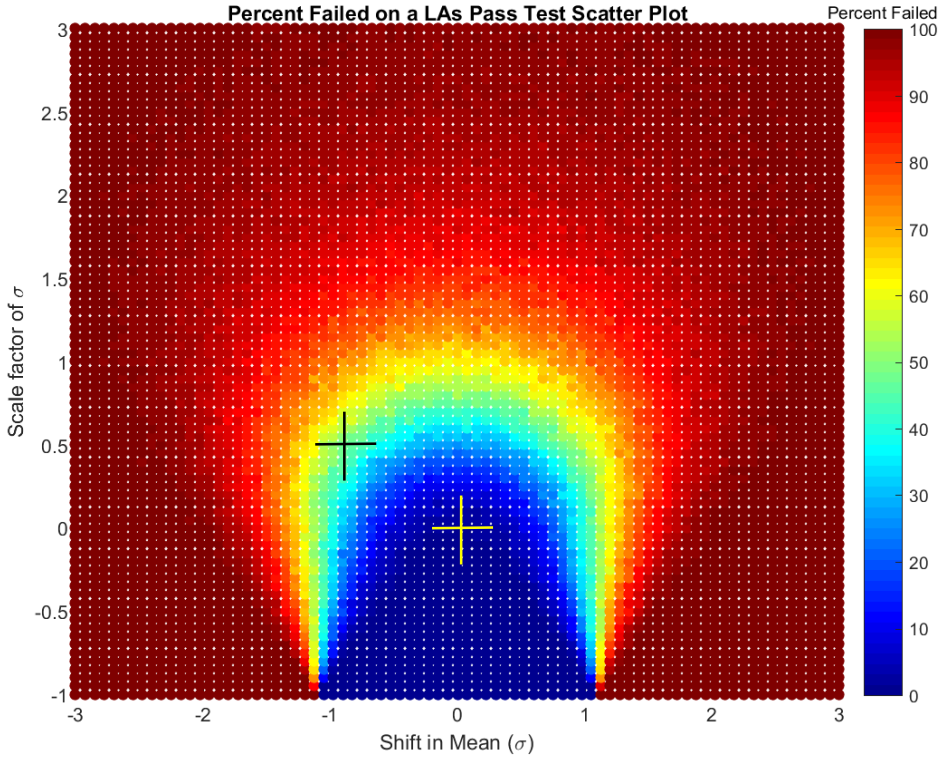
Witness for Statistical Process Control

Simulation is used to evaluate small sample statistical methods for witness specimen acceptance

Design acceptance criteria for the following:

- Keep process in family
- Minimize false negative acceptance results
- Protect the design values witnessed
- Protect the inferred design values





Summary of Points

1. Assuring AM product integrity requires classic process control rigor:
   - Clear definition of the AM process and its metrics
   - Evaluation of the AM process relative to the metrics

2. Open loop AM technologies rely upon passive observation of metrics or post-build evaluation of witness specimens
   - Evolving AM monitoring technologies will provide better methods

3. Key metrics within the AM process
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Thank You

Additive Manufacturing at MSFC